Soil Moisture Feedbacks to Precipitation in Southern Africa

BENJAMIN I. COOK

Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia

GORDON B. BONAN AND SAMUEL LEVIS

National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 3 October 2005, in final form 19 December 2005)

ABSTRACT

The effects of increased soil moisture on wet season (October–March) precipitation in southern Africa are investigated using the Community Climate System Model version 3 (CCSM3). In the CTRL case, soil moisture is allowed to interact dynamically with the atmosphere. In the MOIST case, soil moisture is set so that evapotranspiration is not limited by the supply of water. The MOIST scenario actually results in *decreased* precipitation over the region of perturbed soil moisture, compared to CTRL. The increased soil moisture alters the surface energy balance, resulting in a shift from sensible to latent heating. This manifests in two ways relevant for precipitation processes. First, the shift from sensible to latent heating cools the surface, causing a higher surface pressure, a reduced boundary layer height, and an increased vertical gradient in equivalent potential temperature. These changes are indicative of an increase in atmospheric stability, inhibiting vertical movement of air parcels and decreasing the ability of precipitation to form. Second, the surface changes induce anomalous surface divergence and increased subsidence. This causes a reduction in cloud cover and specific humidity above 700 hPa and results in a net *decrease* of column-integrated precipitable water, despite the increased surface water flux, indicating a reduction in moisture convergence. Based on this and a previous study, soil moisture may act as a negative feedback to precipitation in southern Africa, helping to buffer the system against any external forcing of precipitation (e.g., ENSO).

1. Introduction

Precipitation in southern Africa is sensitive to remote patterns of sea surface temperature (SST) variability, especially during the austral summer period (October–March; Richard et al. 2000; Mason 2001; Richard et al. 2001). Typically, warmer SSTs in either the equatorial Pacific (i.e., ENSO events) or southern Indian Ocean are associated with below-normal rainfall during the summer wet season (Reason and Rouault 2002). Because changes in these SSTs may be a signature of anthropogenic climate change, there is some speculation that the near future may see increased desiccation and/or occurrence of droughts in southern Africa (Hoerling et al. 2006). Any remote forcing of precipitation, however, is likely to be modulated by the state of the land surface. One land surface property known to influence precipitation processes over a wide variety of spatial and temporal scales is soil moisture (Anthes 1984; Dai et al. 1999; Nicholson 2000).

The influence of soil moisture on climate and atmospheric processes can be strong and has been used to explain the prolonging and persistence of drought (Oglesby and Erikson 1989; Hong and Kalnay 2000), enhancement of low-frequency climate variability (Zeng et al. 1999), and the strength and location of the African easterly jet (Cook 1999). The typical hypothesis regarding soil moisture and precipitation invokes a positive feedback loop: wetter soils cause an enhanced moisture flux into the atmosphere from the surface, leading to greater specific humidity, increased cloud cover, and enhanced precipitation over the region (i.e., the so-called precipitation recycling). In addition to supplying moisture directly for precipitation, the moisture flux from the surface may also increase moisture convergence into the region as the surface moisture condenses and releases heat in the atmosphere and

Corresponding author address: Benjamin Cook, Department of Environmental Sciences, University of Virginia, 291 McCormick Rd., Charlottesville, VA 22903.
E-mail: bc9z@virginia.edu

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drives a more vigorous circulation, such as that seen in monsoon regions (Webster 1987). These processes have been studied in a variety of regions, including the continental midlatitudes (Koster et al. 2003; D'Odorico and Porporato 2004), the Sahel region of West Africa (Nicholson 2000), and the Middle East (Anthes 1984). Wetter soils also typically decrease the surface albedo, which may lead to greater net radiation, increased rising motion, and increased moisture convergence (Charney 1975; Eltahir 1998). This mechanism has only recently been investigated but, in certain cases, may be even more important than precipitation recycling for enhancing precipitation (Levis et al. 2004).

Recent evidence suggests, however, that there may exist a *negative* soil moisture feedback to precipitation in southern Africa (New et al. 2003). This hypothesis argues that increased soil moisture results in reduced sensible heating, leading to increased stability of the lower atmosphere and reduced moisture convergence from the surrounding oceans. This was investigated briefly by New et al. (2003) using a regional climate model simulation for a single season. Here we expand on their modeling experiments with a multiyear simulation using a coupled land surface model and atmosphere general circulation model with interannual climate variability in the form of observed sea surface temperatures. Section 2 describes the models used and section 3 explains the experimental setup. Section 4 describes the results. Section 5 includes an in-depth discussion and interpretation of the results.

2. The model

The atmospheric model is the Community Atmosphere Model version 3 (CAM3). This model is the sixth-generation of the atmospheric general circulation models developed by the climate community in collaboration with the National Center for Atmospheric Research. The model features improvements to the parameterizations of moist processes, radiation processes, and aerosols (Collins et al. 2004, 2006) compared with its predecessor, CAM2. The model was run using Eulerian spectral dynamics with T42 spectral truncation (approximately 2.8° in latitude and longitude) with 26 levels in the vertical and a 20-min time step. The land model is the Community Land Model version 3 (CLM3). This model simulates energy, moisture, and momentum fluxes between land and atmosphere, the hydrologic cycle at the land surface, and soil temperature (Bonan et al. 2002; Oleson et al. 2004; Dickinson et al. 2006). CLM3 operates on the same spatial grid as CAM3.

Figure 1 shows monthly climatological precipitation for southern Africa from the control simulation, compared against precipitation from the Wilmott–Matsura dataset (Willmott and Matsuura 2000). Precipitation for this region is slightly overpredicted by the model, but in general is in good agreement with the observations.

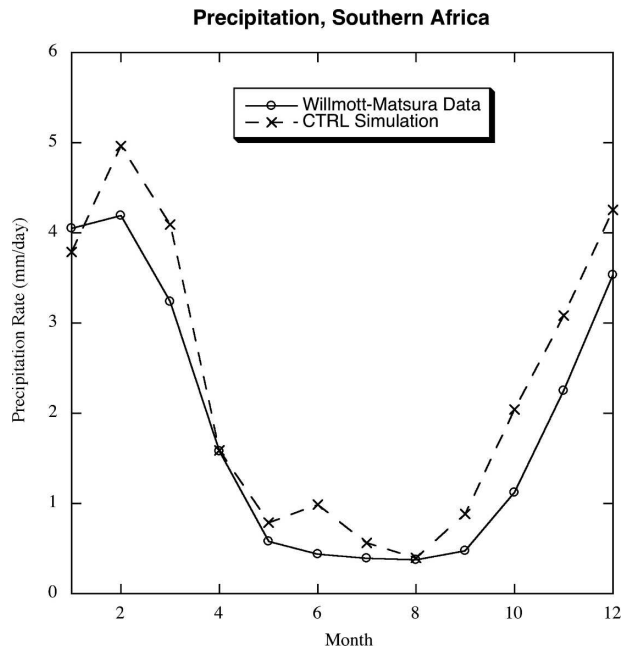

FIG. 1. Monthly climatological precipitation rate (mm day^{-1}) from the CTRL run of the model (dashed line) and from the Wilmott–Matsura dataset (solid line) for southern Africa south of 10°S.

3. Experimental setup

All simulations were run with observed SSTs from 1979 to 2000. The types of vegetation in a model grid cell, their fractional coverage, and their leaf area index were prescribed from satellite data (Bonan et al. 2002; Oleson et al. 2004; Dickinson et al. 2006), but otherwise the land surface was allowed to interact with the atmosphere (except for soil moisture in the MOIST scenario). The first 5 yr (1979–83) of each simulation were discarded as spinup and the 17 yr after (1984–2000) were used for comparison between the scenarios. All figures henceforth represent differences between simulations averaged over this latter period.

We conducted several model runs, designed to assess the impact of soil moisture on wet season precipitation through both soil albedo effects and moisture flux. The wet season (October–March) is our primary interest. The vast majority of the rainfall in this region falls during this season (Fig. 1) and rainfall variability during this period has the greatest influence on ecosystems, agriculture, and human activities. In our CTRL experiment, soil moisture was allowed to dynamically respond

and interact with the atmosphere. In our MOIST experiment, the soil moisture for every grid cell in Africa south of 10°S was set to field capacity. Within the scope of the model, this effectively created conditions where the flux of water from the surface to the atmosphere (evapotranspiration) was no longer limited by the supply of water (replicating conditions from New et al.'s 2003 experiments). We also ran variants of these experiments with the dependency of the soil albedo on soil moisture turned off. These experiments did not significantly impact precipitation anomalies relative to the experiments with albedo dependence included and, hence, will not be discussed. For interpretation purposes, we have broken the wet season into two periods: October–December (OND) and January–March (JFM). Because the wet season was our primary interest, the following analysis focuses on the precipitation response during these two periods and the dry season (April–September) will not be discussed.

4. Results and analysis

Table 1 shows a spatially averaged summary of surface variables for the MOIST and CTRL cases for the OND and JFM periods, spatially averaged south of 10°S. All figures (other than Fig.1) show temporally averaged differences between the MOIST and CTRL case for a variety of variables, with negative contours dashed and shaded in gray. Areas where the difference between the two cases was significant at the $p < 0.05$ level (determined using a Student's t test) are stippled.

a. Surface characteristics and precipitation

As expected, the two simulations show stark differences in their surface energy balance (Table 1): the MOIST simulation shows a strong shift toward reduced sensible heating and increased latent heat flux, relative to CTRL. Despite the increase in latent heating, and the consequent increase in moisture flux to the atmosphere, a comparison of the two scenarios shows a sharp decrease in precipitation rate over a large area of southern Africa (Fig. 2). A narrow strip of positive precipitation anomalies occurs along the west coast. This region is normally very dry year-round: little precipitation occurs in any month and actual evapotranspiration is very small compared to potential evapotranspiration. The imposed soil moisture anomalies and precipitation responses are therefore highly unrealistic in this area and will not be discussed.

The region of significantly reduced precipitation covers most of the region of perturbed soil moisture and is persistent in both the OND and JFM seasons, although the anomalies are stronger in the OND season. This is contrary to what we would expect from the precipitation recycling paradigm or other positive feedbacks between soil moisture and precipitation referenced previously. To discover the reason for the precipitation response in our model we must look closer at the atmospheric response.

TABLE 1. Summary of surface characteristics for each period (OND and JFM) and each scenario (MOIST and CTRL). All values represent temporal averages over the 1984–2000 period and spatial averages for the region south of 10°S. Variables are incident solar radiation, absorbed solar radiation, incident longwave radiation, emitted longwave radiation, sensible heat flux (SHF), latent heat flux (LHF), air temperature at 2 m, and surface pressure.

Avg surface conditions: OND				
Surface variables	MOIST	CTRL	Diff	Units
Incident solar	226.78	290.30	−63.52	W m^{-2}
Absorbed solar	192.82	236.44	−43.62	W m^{-2}
Incident longwave	362.06	357.21	4.85	W m^{-2}
Emitted longwave	410.98	442.71	−31.73	W m^{-2}
SHF	15.42	50.07	−34.65	W m^{-2}
LHF	116.00	93.82	22.18	W m^{-2}
2-m temperature	291.47	295.73	−4.26	K
Surface pressure	94 594	94 273	321.00	Pa
Avg surface conditions: JFM				
Surface variables	MOIST	CTRL	Diff	Units
Incident solar	224.82	253.92	−29.10	W m^{-2}
Absorbed solar	184.62	204.24	−19.62	W m^{-2}
Incident longwave	377.11	374.77	2.34	W m^{-2}
Emitted longwave	423.79	437.39	−13.60	W m^{-2}
SHF	18.48	33.76	−15.27	W m^{-2}
LHF	119.25	111.88	7.37	W m^{-2}
2-m temperature	293.70	295.37	−1.67	K
Surface pressure	94 431	94 253	178.00	Pa

b. Atmospheric stability

The increased latent heat flux in the MOIST scenarios results in cooler surface temperatures and increased surface pressure (Table 1). These changes at the surface act to increase atmospheric stability, as expressed by a reduction in boundary layer height and an increase in the vertical gradient of equivalent potential temperature (Fig. 3). Stability exerts a strong influence on precipitation processes through its modulation of vertical movement. Increasingly stable conditions (as seen in our MOIST simulations) impede the vertical movement of air parcels, and can thus reduce the occurrence of precipitation by preventing moist air from reaching levels in the atmosphere where it can rain out.

c. Regional-scale dynamics

In addition to changes in the lower atmosphere and boundary layer, the MOIST case also shows changes in

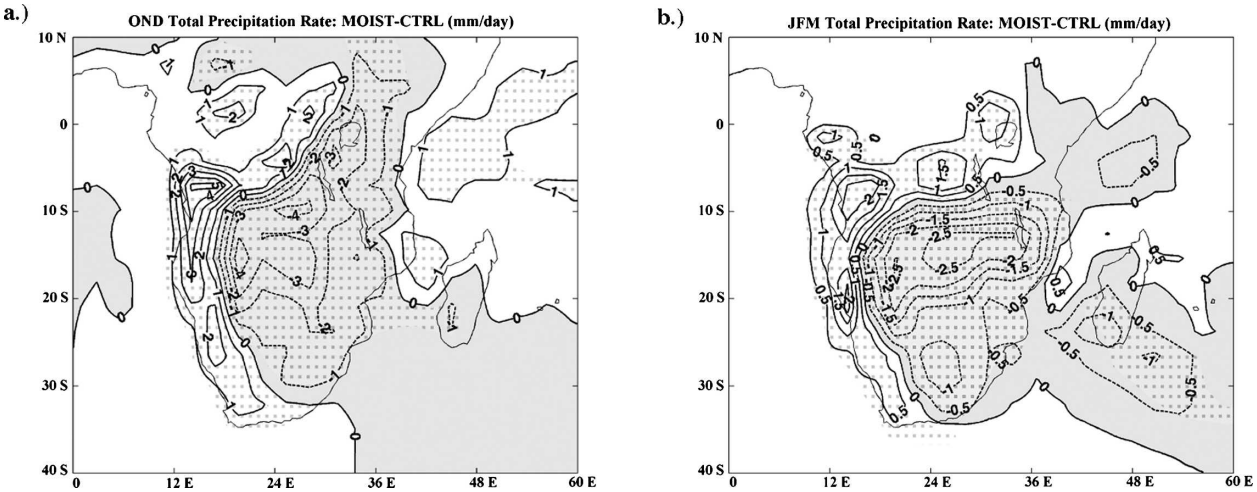

FIG. 2. Differences in precipitation rate (mm day^{-1}), MOIST minus CTRL, for (a) OND and (b) JFM. See text for definition of stippled areas in this and the remaining figures.

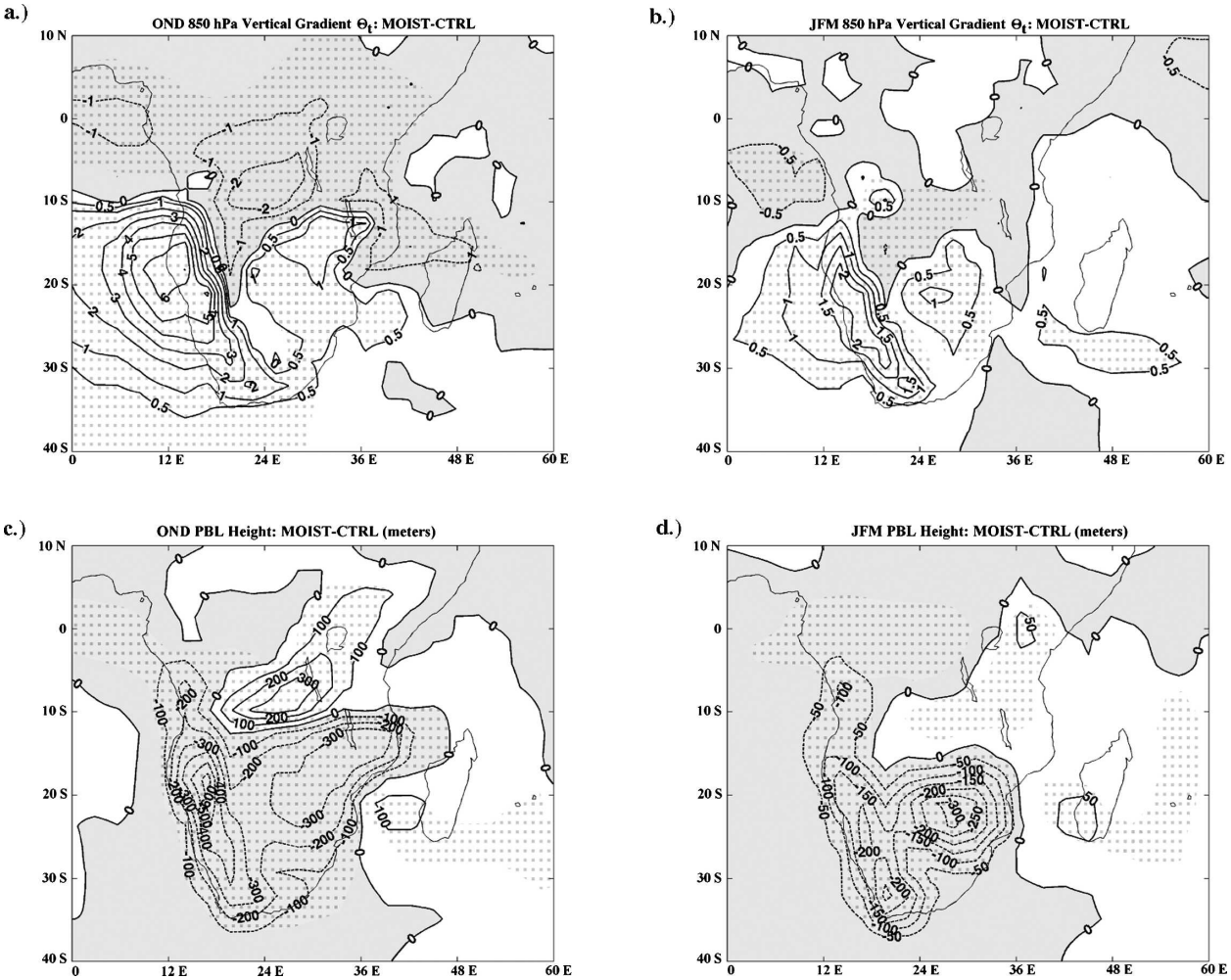

FIG. 3. Differences in atmospheric stability indicators, MOIST minus CTRL. Vertical gradient in equivalent potential temperature centered at 850 hPa for (a) OND and (b) JFM. Planetary boundary layer height (m) for (c) OND and (d) JFM.

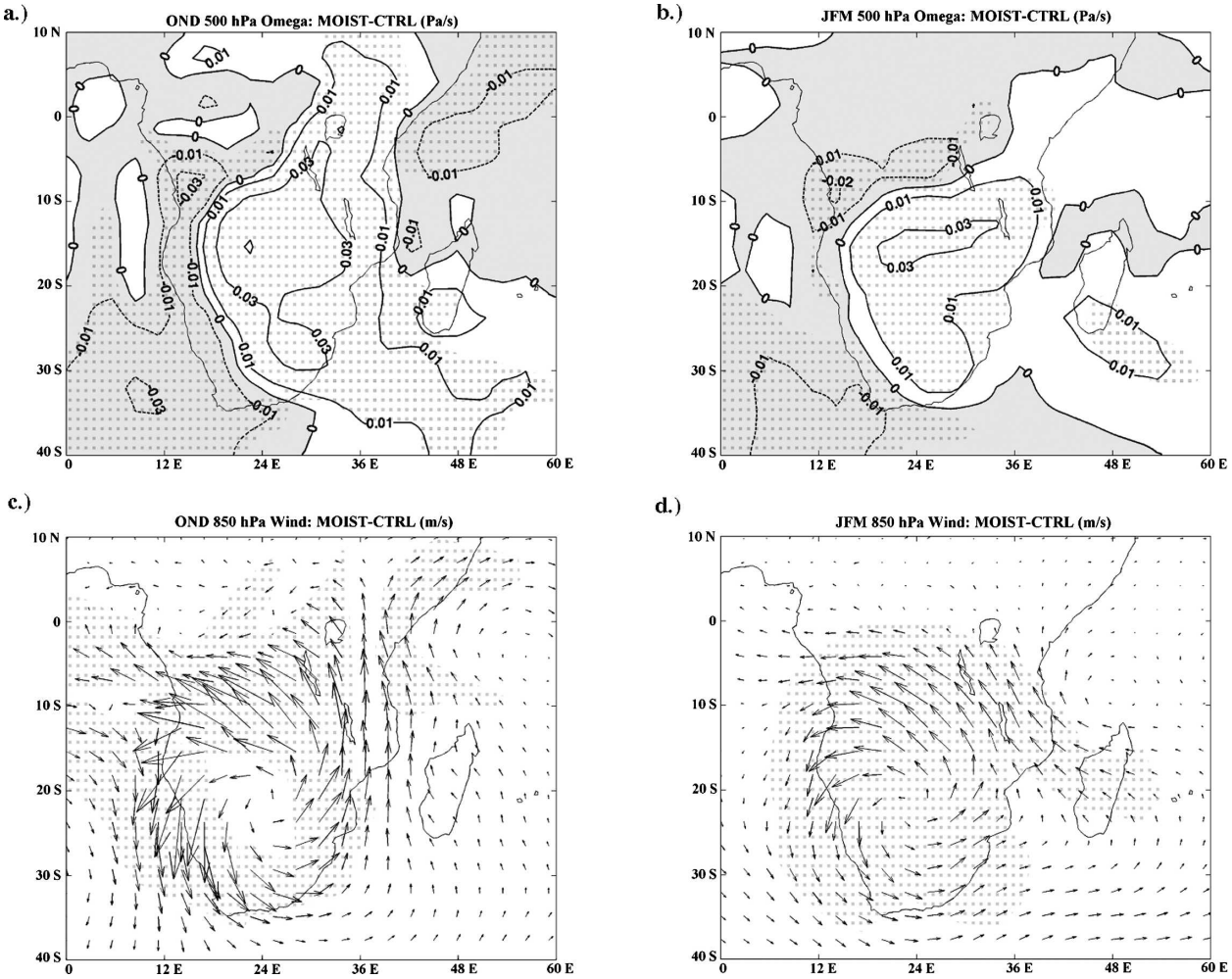

FIG. 4. Differences in large-scale dynamics, MOIST minus CTRL. The longest arrow on the wind plots indicates a wind anomaly of $\sim$7 m s^{-1}. Omega (Pa s^{-1}) at 500 hPa for (a) OND and (b) JFM. Winds (m s^{-1}) at 850 hPa for (c) OND and (d) OND.

the large-scale dynamics (Fig. 4). The anomalously high surface pressure induces anomalous surface divergence, seen in the increased anticyclonic nature of the 850-hPa winds. This, in turn, leads to enhanced subsidence (positive omega values) that extend through to the 500-hPa level (omega values at 850 hPa, not shown, are similar to the 500-hPa values shown). Subsidence suppresses convection, inhibiting the ability of precipitation to form, similar to the effect of increased atmospheric stability.

The change in dynamics also has ramifications for the supply of moisture, as seen in Figs. 5–6. Figure 5 shows cloud cover at two different levels: low clouds below 700 hPa (Figs. 5a,b) and high clouds from 400 to 50 hPa (Figs. 5c,d; medium-level clouds between 700 and 400 hPa are not shown, but are similar to the high clouds plots). There is a fairly uniform increase in low clouds over the same area as the perturbed soil moisture. This is from the increased surface water flux. Above this level, however, there are sharp reductions in cloud cover over much of the area of perturbed soil moisture. The reduced cloud cover even extends into the Indian Ocean (the major moisture source for southern Africa). Unsurprisingly, the changes in cloud cover overlap quite closely to changes in specific humidity (Fig. 6) showing an increase in near-surface (850 hPa) moisture associated with enhanced moisture flux from the land surface (Figs. 6c,d). At the 500-hPa level, though, over an area similar in extent to the high cloud fields, there is a reduction in specific humidity in the MOIST case (Figs. 6a,b). If we examine the difference in column-integrated precipitable water (Fig. 7), we see that the MOIST case overall shows a net *reduction* in precipitable water. Since the MOIST case has a higher surface water flux through increased latent heating, the deficit must come from reduced moisture convergence, a

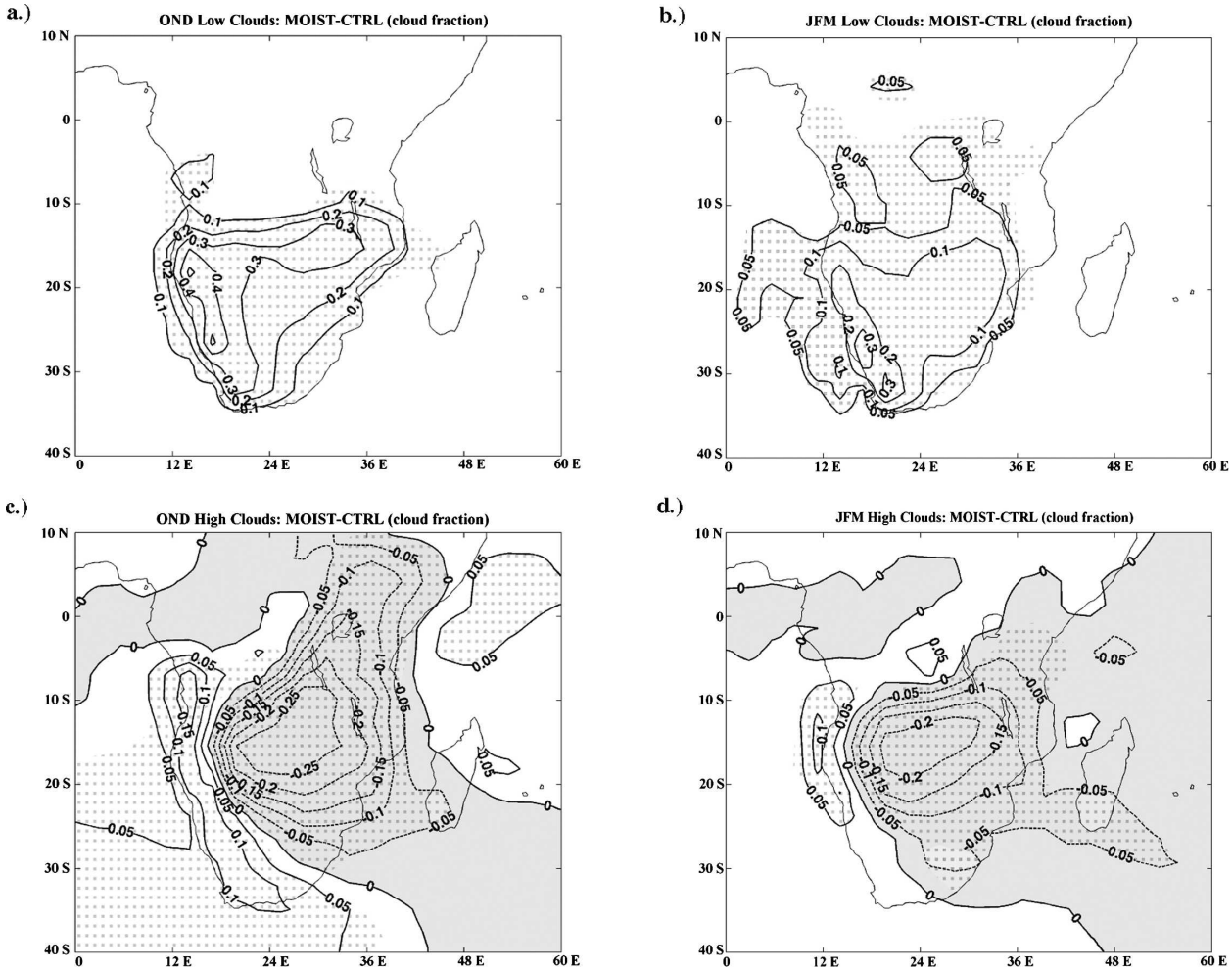

FIG. 5. Differences in cloud fraction (dimensionless), MOIST minus CTRL. Low-level clouds for (a) OND and (b) JFM. High-level clouds for (c) OND and (d) JFM.

premise supported by the change in dynamics, cloud fields, and specific humidity fields.

5. Discussion

Our study is an extension and validation of the preliminary work in New et al. (2003). Here we have expanded their investigation, with multiyear model runs including interannual climate variability in the form of observed SSTs. Overall, our results show a remarkable similarity to the results of New et al. (2003). The large area of precipitation anomalies is reproduced. In addition, the same mechanisms appear to explain the precipitation changes in our experiments.

In our MOIST scenario, the increased soil moisture resulted in an increased latent heat flux and increased moisture in the near-surface and lower atmosphere, as reflected in the 850-hPa specific humidity and cloud fields (Figs. 5a,b and Figs. 6c,d). However, the surface changes also resulted in a reduced boundary layer height and increased vertical gradient in equivalent potential temperature (Fig. 3), indicating increased atmospheric stability that can inhibit precipitation from forming. The shift in the energy balance from sensible heating to latent heating also led to increased surface pressure, inducing enhanced subsidence and anomalous surface divergence (Fig. 4). This change in atmospheric dynamics led to decreased moisture advection from the oceans (as can be seen in the upper-level specific humidity and cloud fields, Figs. 5c,d and Figs. 6a,b), and an actual net *reduction* in column-integrated precipitable water (Fig. 7). This change in regional-scale dynamics is quite similar to how SST variability in the tropical Pacific (the El Niño–Southern Oscillation) and southern Indian Ocean influence precipitation over the region (Mason and Jury 1997; Mason and Tyson 2000;

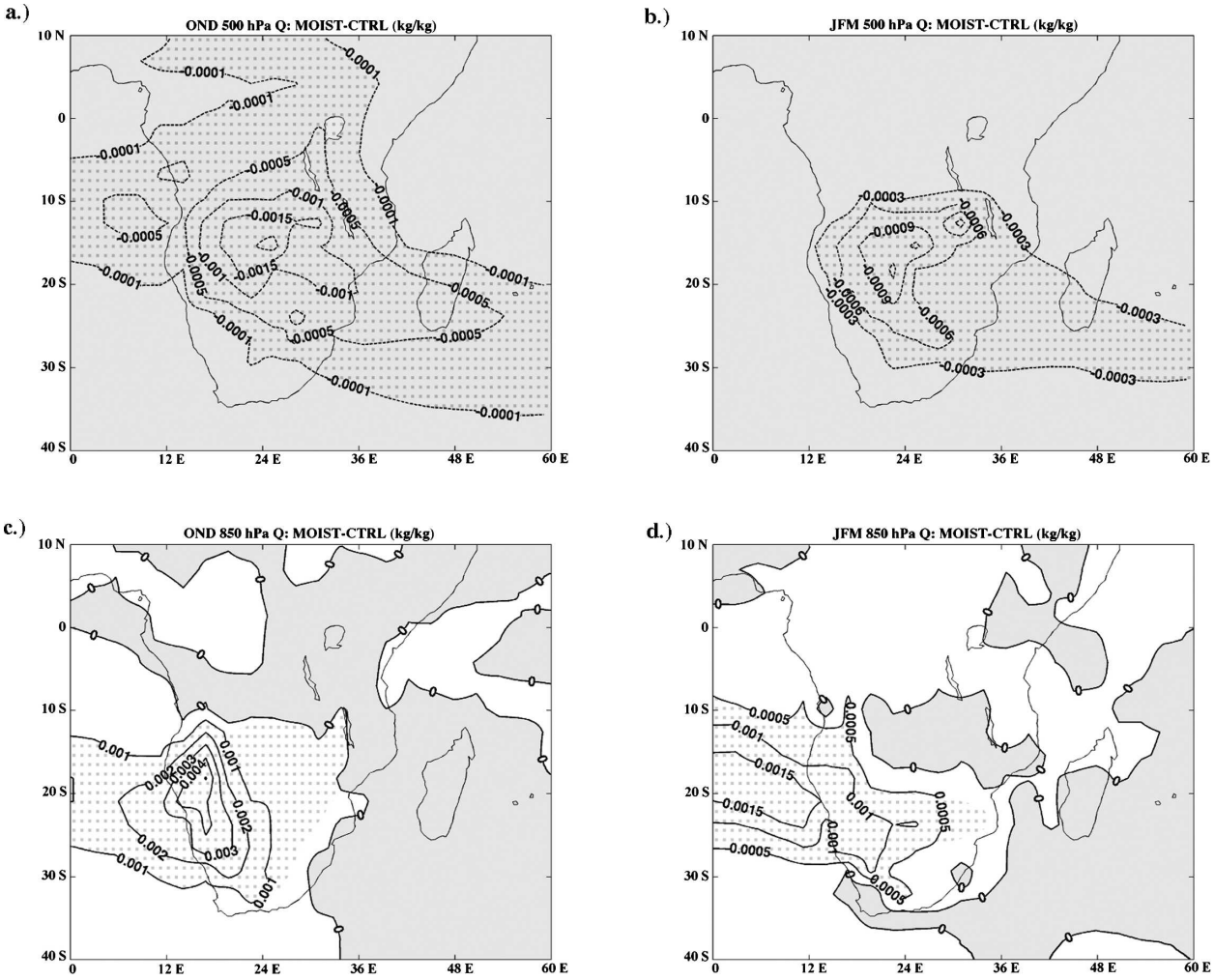

FIG. 6. Differences in specific humidity (kg kg^{-1}), MOIST minus CTRL. At 500 hPa for (a) OND and (b) JFM. At 850 hPa for (c) OND and (d) JFM.

Richard et al. 2000; Mason 2001; Reason and Rouault 2002). The positive soil moisture anomalies therefore act to reduce precipitation through two complementary mechanisms, by decreasing the ability to form precipitation (via increased atmospheric stability and enhanced subsidence) and decreasing the supply of moisture for precipitation (via decreased moisture convergence). Our results suggest that the result New et al. (2003) obtained may not be model dependant, but may be a robust feature of the climate system in southern Africa.

The atmospheric responses during the early (OND) and late (JFM) portions of the wet seasons are qualitatively similar. Anomalies tend to be higher during OND, but otherwise reflect the same mechanisms and atmospheric responses operating during JFM. The higher anomalies suggest that wet season precipitation may be more sensitive to the soil moisture state during the beginning of the wet season because of the naturally lower soil moisture and precipitation (as reflected in out CTRL simulation). Still, the anomalies persist throughout both halves of the season, implying that the state of the soil moisture exerts an important influence throughout the entire wet season.

Validation of studies such as this relies on the availability of high-quality datasets that are spatially comprehensive and cover a long time span. While precipitation data for southern Africa is readily available and of fairly good quality (New et al. 2000), soil moisture data is largely unavailable. Data from most monitoring sites only extends back a few years, and the high degree of spatial heterogeneity in soil moisture, combined with the paucity of coverage, make these datasets largely unsuitable for validation purposes. Some gridded datasets are available (Fan and Van den Dool 2004) but these are largely based on models driven almost en-

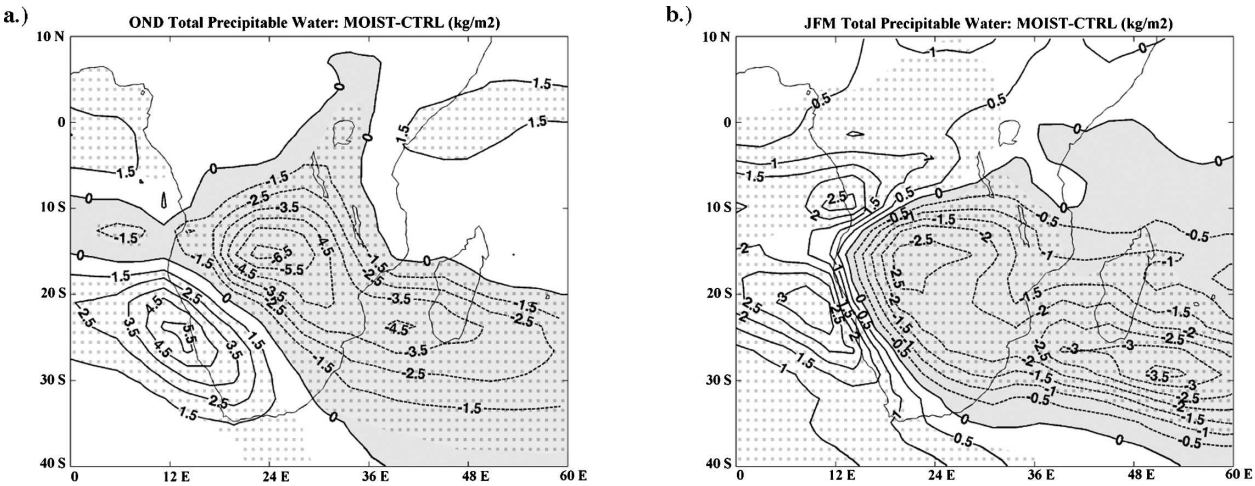

FIG. 7. Differences in column-integrated total precipitable water (kg m^{-2}), MOIST minus CTRL, for (a) OND and (b) JFM.

tirely by precipitation inputs. We can do a limited assessment by comparing precipitation in southern Africa against precipitation in areas where positive soil moisture and land surface feedbacks are thought to be operating. For example, in sharp contrast to areas such as the Sahel region, the precipitation record in southern Africa shows no coherent persistent regimes and little low-frequency variability at decadal scales and longer (Richard et al. 2001; Fauchеareau et al. 2003; Jury et al. 2004). This at least opens up the possibility that there may be some negative feedback operating in southern Africa. Positive feedbacks, such as in the Sahel region, would tend to push the precipitation and soil moisture in the system toward either a persistent "wet" state or a persistent "dry" state, with a decreased probability of occurrence of intermediate conditions (D'Odorico and Porporato 2004). Negative feedbacks, however, act to stabilize a system, essentially damping variance, shifting the system to a more centered distribution. If we work on the linear assumption that dry soil moisture anomalies would induce precipitation anomalies of nearly equal and opposite sign (as was found in the New et al.'s 2003 experiments), it seems feasible that negative soil moisture feedbacks within southern Africa may be acting to ameliorate any externally induced trends toward drought.

Examination of soil moisture–precipitation feedbacks requires a consideration and understanding of the boundary conditions of the system being studied. Many previous soil moisture feedback studies have focused on midcontinental systems, such as the North American Great Plains, where much of the moisture comes from localized precipitation recycling. These areas are typically very far from any oceanic source of water and therefore rely very strongly on internal cycling of water in the system, rather than importation from other areas. Ideas developed from these studies helped shape the default line of thought that more soil moisture equates more precipitation. But recent research has shown that this is not at all straightforward. Findell and Eltahir (2003) identified several regions in the United States where positive soil moisture anomalies may be associated with increased or decreased precipitation and regions where the soil moisture state had a negligible influence on precipitation. Others have conducted modeling experiments similar to this study for the Indian monsoon region (Meehl 1994; Douville et al. 2001), with results and mechanisms consistent with the results presented here. Our work contributes to this body of literature by expanding the analysis to southern Africa, where heretofore there have been few investigations into land surface feedbacks to regional climate.

Acknowledgments. The National Center for Atmospheric Research is sponsored by the National Science Foundation. All model simulations were done on a CSL allocation. BIC acknowledges the material and intellectual support of M. E. Mann, T. M. Smith, H. E. Epstein, and the Department of Environmental Sciences at the University of Virginia.

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